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STATUS OF BEAM-BEAM STUDIES FOR THE HIGH-LUMINOSITY LHC*

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Abstract

Optimizing the configuration of an operational cycle of a collider such as the LHC is a complex process, requiring various simulation studies. In particular, Dynamic Aperture (DA) simulations, based on particle tracking, serve as indispensable tools for achieving this goal. In the framework of the High-Luminosity LHC (HL-LHC) studies, our primary focus lies in performing parametric beam-beam DA simulations for the critical phases of the collision process, which includes the collapse of the beam separation bump, as well as the start, and the end of the luminosity levelling. In this paper, we present the status of our ongoing studies for different optics and filling schemes, and we comment on how they could guide the orchestration of the operational settings along the luminosity levelling phase of the HL-LHC cycle.

INTRODUCTION

The HL-LHC project represents a significant endeavour in particle physics, aiming at reaching an integrated luminosity of 250 fb^{-1} of proton-proton collisions per year in both ATLAS and CMS experiments [1]. Attaining this objective will become possible due to several contributing factors. These include enhanced beam intensity and brightness enabled by the LHC Injector Upgrade [2], the implementation of Achromatic Telescopic Squeeze (ATS) optics enabling better chromatic control of the beam size at the main Interaction Points (IPs) [3], a larger squeeze at the IPs due to stronger final focusing magnets [1], and the advancement of innovative technologies for beam manipulation, such as the integration of crab cavities to counteract the geometric loss of luminosity due to the large half-crossing angle (250 µrad) in IPs 1 and 5 [4, 5].

Central to the success of this initiative lies the optimization of the Dynamic Aperture (DA), a commonly used metric in accelerator physics, crucial for ensuring adequate beam lifetime in the collider. Given some collider optics and corresponding beam parameters, the DA is numerically computed and reflects the single particle stability of a beam over 1 M turns. It has been shown that a DA of at least 5.5 σ to 6 σ is sufficient for maintaining an acceptable beam lifetime during LHC operation [6].

Beam lifetime can be greatly degraded by beam-beam effects, which are collective electromagnetic interactions between particles within the colliding bunches. More specifically, Long-Range (LR) and Head-On (HO) interactions can significantly affect the vertical and horizontal oscillation spectra of individual particles, leading to the excitation of various resonances and subsequent particle losses. Given the higher brightness of the HL-LHC beams, beam-beam effects are expected to be the main driver of DA degradation [7, 8].

In this paper, we thoroughly examine the current state of beam-beam DA studies for the HL-LHC for different optics, corresponding to the different phases of the cycle. Overall, we study the critical steps of the collision process at top energy (7 TeV), including the start and end of the collapse of the beam separation bump, as well as the start and end of the luminosity levelling phase.

DA PARAMETRIC STUDIES

HL-LHC parameters for simulations are shown in Table 1, while optics-dependent parameters are presented in Table 2. We selected a set of optics files (listed in [9]) corresponding to a scenario revolving mainly around round optics ($\beta_x = \beta_y$ at the IPs). So far, positive octupole polarities have been the baseline [10]. Here, we focus on negative polarities since they show promising results for impedance and DA. Simulations are weak-strong and implemented using Xsuite, a beam physics simulation framework developed at CERN [11].

Table 1: Baseline simulation parameters. The crossing angle is always horizontal in IP1, and vertical in IP 2, 5 and 8. Since the optics are always round in IPs 2 and 8, $\beta^*_{x,y}$ is identical in the vertical and horizontal planes.

Parameter	Value
HL-LHC layout version	1.6
Beam energy E	7 TeV
RMS bunch length σ_z	7.61 cm
Coupling $\lvert C^-\rvert$	10^{-3}
Chromaticity $Q'_{x,y}$	15
$IP_{1/5}$ half crossing angle $\Phi_{1,5}/2$	250 µrad
IP_2 half crossing angle $\Phi_2/2$	−170 µrad
IP_8 half crossing angle $\Phi_8/2$	170 µrad
Relative momentum deviation $\delta p/p$	27×10^{-5}
$\beta^*_{x,y}$ in $IP_{2/8}$	1.5/10 m
Number of bunches	2760
Number of collisions in IP 1/5	2748/turn
Number of collisions in IP 2	2492/turn
Number of collisions in IP 8	2574/turn

Beam-beam effects may vary widely from bunch to bunch depending on the details of the bunch encounter schedule, and therefore on the filling scheme. For our simulations, we select a bunch colliding in all four IPs, and subject to the highest possible number of LR encounters. That is, we select the worst possible bunch in terms of beam-beam effects, assuming that this would be the most conservative pick for the DA. We checked this hypothesis *a posteriori* with

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Table 2: Optics-dependent simulation parameters, along the collision cycle. $\mathscr{L}_{1,5}$ corresponds to the luminosity in IPs 1 and 5, ε to the normalized emittance (same in horizontal and vertical planes), I to the octupoles current, N_b to the bunch population, $\beta^*_{\mathrm{IP}_{1,5}}$ to the optics β function at the collision point in IPs 1 and 5, ATS to the Achromatic Telescopic Squeeze factor (also referred as tele-index), CC to the crab-cavity angle. When two values are present, whether for β^* or tele-index, they correspond to the horizontal and vertical plane, respectively, in IP 1 (and vice-versa in IP 5).

Step	Optics	$\mathscr{L}_{1,5}$ (10^{34} cm^{-2}/s)	ε (µm)	I (A)	N_b (10^{11} p$^+$/b)	$\beta^*_{\mathrm{IP}_{1,5}}$ (m)	ATS	CC (µrad)
Collapse start	round	0	2.3	-300	2.3	1.1	1	0
Collapse start	flat	0	2.3	-150	2.3	1.8/0.9	0.28/0.56	0
Collapse end	round	2.45	2.3	-300	2.2	1.1	1	0
Collapse end	flat	2.36	2.3	-150	2.2	1.8/0.9	0.28/0.56	0
Levelling start	round	5	2.3	-60	2.2	0.58	1	-96.6
Levelling end	round	5	2.5	-60	1.1	0.15	3.33	-190

a bunch-by-bunch scan for the end-of-levelling optics [9], revealing that the selected bunch is in the last decile in terms of DA. Reassuringly, it also shows that the difference in DA for the actual worst bunch is smaller than 0.2 σ, well within the statistical noise of the analysis. An additional scan [9] also shows that, as expected, results are similar for the worst bunch of Beam 1 and the worst bunch of Beam 2.

For each optics, we mainly look for the optimal Working Point (WP), i.e. the combination of horizontal and vertical tunes (Q_x, Q_y) that yields the highest DA. It is however paramount to consider that, when doing a tune scan, a split — the difference between the fractional part of the horizontal and vertical tunes — of at least 5×10^{-3} is required to avoid loss of transverse Landau damping, hence beam instabilities from impedance, due to $x - y$ coupling [12]. The upper tune split diagonal is represented as a dashed blue line in all relevant plots. In addition, we choose a target of 6 σ, represented as a green contour in all relevant plots.

Beam Separation Collapse

For beam stability, the most critical phase of the cycle is the collapse of the beam separation bumps. During this phase, beams go from being fully separated in all IPs, to fully HO in IPs 1 and 5, partially HO in IP 8 to reach a target luminosity of 2×10^{33} cm^{-2}/s, and partially HO in IP 2 to keep 5 σ of separation.

At the start of collapse, Landau damping is almost uniquely coming from the strongly powered octupoles [13]. As the separation bump reduces, the beam-beam HO tune spread increases, providing a new source of Landau damping. However, the arc octupoles cannot be ramped down as fast as the tune spread changes. This means that the DA gets constrained by both high octupoles, and beam-beam effects.

An additional difficulty faced during collapse is due to the use of crab cavities (CCs). The CCs allow to compensate for the luminosity loss due to the geometrical factor induced by the crossing angle. They are, however, detrimental to transverse impedance, due to their narrow-band resonant modes, combined with the large β functions in the crabbing plane at their location. During the critical phase of collapse, this effect can be mitigated by using flat optics,

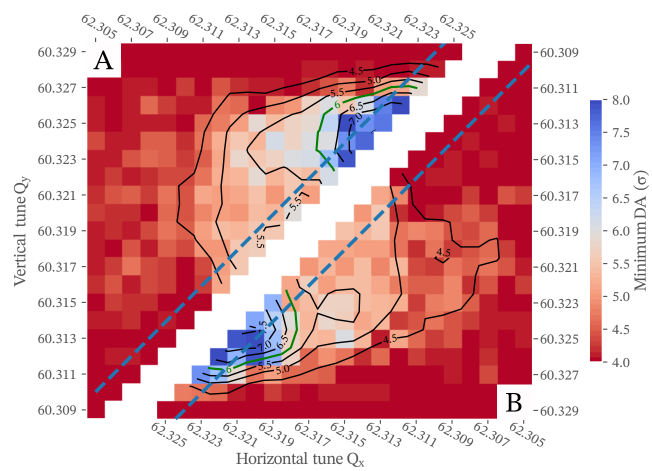

Figure 1: DA as a function of horizontal and vertical tunes at the end of collapse for round (A) and flat (B) optics. Note the axes reversal between the two subplots.

with a lower β-function at the CCs in the crabbing plane, therefore improving beam stability [14].

At the start of collapse, simulations [9] show that the situation is very stable (DA>8 σ) for almost all scanned WPs, with both round and flat optics. Conversely, at the end of collapse, the WPs at which the DA gets above the 6 σ target become more limited with both optics (Fig. 1). Note that a lower absolute value of octupole strength is used here for flat optics, as a lower tele-index leads to a larger β-function in the octupoles, hence to an enhanced octupole efficiency for Landau damping. Octupoles at -300A in the round optics are approximately equivalent to -150A in the flat optics.

Increasing the octupole current reveals a reduction of the 6 σ DA region, along with a downward shift of the optimal WPs, for high positive currents (Fig. 2). Impedance is not modelled in our simulations, but this result shows that, although flat optics clearly yield a DA degradation, the 6 σ target can still be reached for octupoles intensities ranging from about -300A to 100A. Considering the scaling of octupolar effects with the ATS factor, the DA picture seems comparable in round and flat optics.

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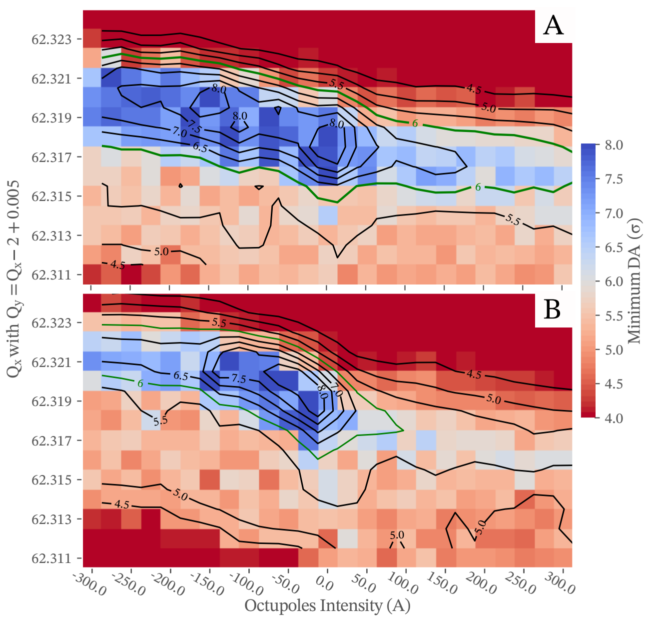

Figure 2: DA as a function of tune and octupole current along the upper tune split diagonal, at the end of collapse for round (A) and flat (B) optics.

Luminosity Levelling

As the beam intensity decays from inelastic protons scattering, the β^* in IPs 1 and 5, along with the separation in IP 8, are progressively reduced to maintain constant target luminosities. This process, called levelling, continues until the minimum β^* is reached in IPs 1 and 5, or the separation is closed in IP8. Then, the optics remain constant, and the luminosity naturally decreases until the beams are dumped.

The start of levelling is usually not a critical phase, as LR effects remain weak since β^* is quite high. To reach the target luminosity level given the optics of Table 2, we consider a CC angle of −96 µrad. This is needed as using the −190 µrad nominal angle of the CC would have led to a luminosity higher than the target, since the considered optics was designed for a luminosity levelling using 2464 bunches. We expect this choice to only marginally modify the resulting DA, compared to a more relaxed optics at full CC crossing. The resulting tune scan is shown in Fig. 3 (A), in which the 6 σ DA target can be reached for several WPs. Conversely, at the end of levelling (Fig. 3 (B)), only few scanned WPs reach the target, overall at lower tunes. Additional scans show that using positive octupoles at the end of levelling yields slightly worse results [9].

Given that the DA target is barely reached at the end of levelling, an emittance blow-up might compromise beam lifetime. This is illustrated in Fig. 4 (A), where the emittance is increased up to $\varepsilon = 2.7$ µm, leading to a DA lower than 6 σ. It is worth noting that, in our simulations, we neglect electron-cloud effects [15]. This effect is expected to be mitigated with a new surface treatment [16], but, depending on the outcome of the treatment, a different filling scheme, featuring fewer bunches, might still be required.

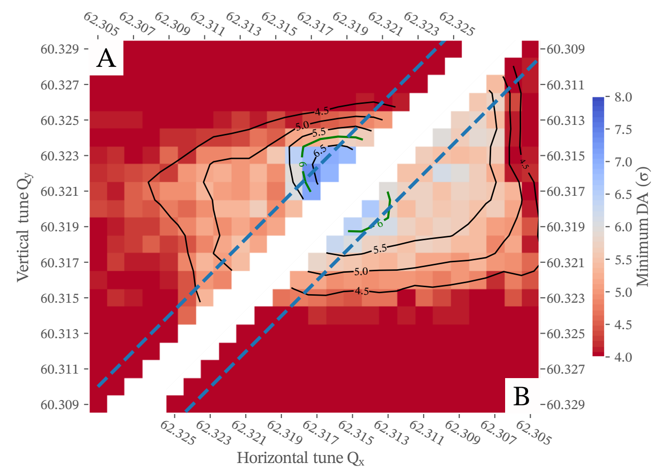

Figure 3: DA as a function of horizontal and vertical tunes, for start (A) and end (B) of levelling.

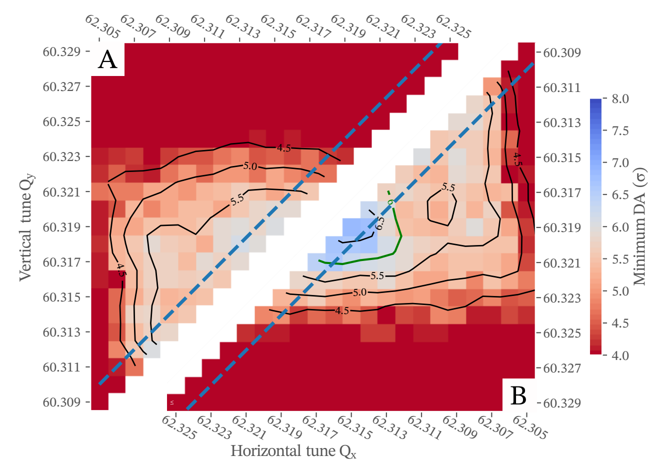

Figure 4: DA as a function of horizontal and vertical tunes, for the end of levelling optics, for a higher emittance ($\varepsilon = 2.7$ µm) than nominal (A), or a filling scheme with less bunches (2464 bunches, B).

This is especially true as significant DA degradation has also been observed due to e-cloud in the (untreated) triplets [17]. Simulation results for a scheme comprising 2464 bunches (with the nominal $\varepsilon = 2.5$ µm) are presented in Fig. 4 (B), showing a large increase of the region above the DA target.

CONCLUSION

Beam-beam DA studies for HL-LHC proton-proton collisions under operational settings show that WPs leading to a reasonable beam lifetime can be found for all the critical phases of the cycle, including the start and end of both the collapse and levelling phases. As expected, negative octupole polarities tend to improve the DA compared to positive ones. During the collapse, round optics tend to yield better results. Some adaptation of the operational configuration, such as phase advance optimization [18] or LR beam-beam compensation using DC wires [19] might still be needed at the end of levelling to ensure a larger DA margin.

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